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Design of the Skybus SB-400 High Capcity Short Range Transport Aircraft

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ISYE 4803: The Skybus SB-400 Short Range Transport Aircraft

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Executive Summary

As air travel becomes more and more affordable and the world economy expands, so does the demand for flights. Major commercial airports and their infrastructure are struggling to keep up with this increased demand. The AIAA has identified this problem and has put out a Request for Proposal for a High Density Short Range Transport Aircraft which can carry 400 people in a two class configuration up to 3,500 nautical miles. The Skybus SB-400 is our clean slate design response to the AIAA's RFP for a High DensityShort Range Transport Aircraft. an increasing part of everyday life. Our focus for the design was to increase efficiency and therefore economics utilizing new technologies in materials for structures, a modern engine selection, as well as optimizing the design for a 700 nautical mile mission by way of aerodynamics and cargo capacity.

Chapter 1: Requirements and Mission Profile

1.1 Introduction

As individual country's economies have advanced and expanded alongside an ever growing globalistic world, air travel has become an increasing part of everyday life. From the way we conduct business to the way cross continental travel expands our world view and onto the way we get the food we eat to the way we conduct war, air travel has had an incalculable impact on the way humanity exists now and will in the future.

This growing demand for commercial air travel has led to an increasing congestion at major airports worldwide and the gate capacity of the airports cannot keep up with the number of flights demanded by the airlines. The problem we seek to solve is both meeting current and future demand between major hubs while reducing airport congestion through a high capacity short range aircraft, the Skybus SB-400.

1.2 Overview

The following section outlines the guidelines set in AIAA's Request for Design Proposal for a high density, short range airliner. The primary design mission is a 700 nmi passenger flight, but the aircraft must be able to complete a 3,500 nmi flight with legal reserves so that will be the design mission profile. The 3,500 nmi passenger flight with reserves is shown below in Figure 1.1. The mission profile requires that fuel for a possible diversion is accounted for in case of bad weather or airport closure. A diversion distance of 150 nmi was assumed for the mission profile, as that will allow the aircraft to reach a diversion airport within 30 minutes at cruise speed.

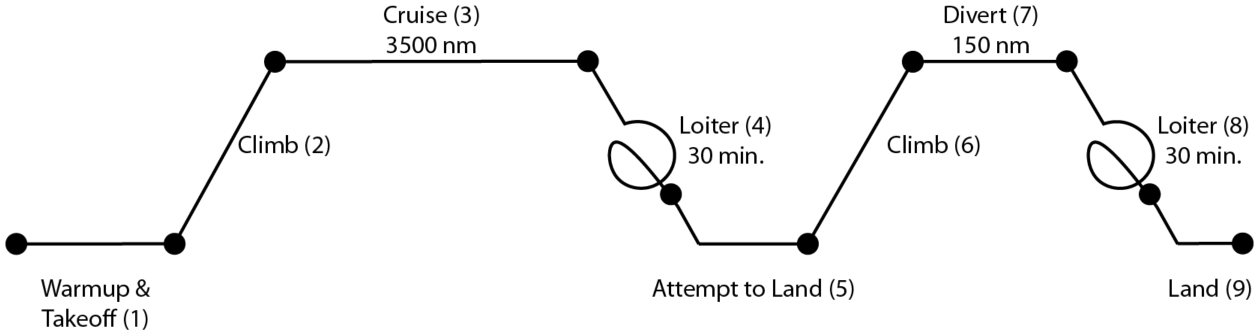

Figure 1.1: Passenger Airliner Mission Profile

1.3 RFP Requirements

General	
RBS	**Requirement**
1	Capable of taking off and landing from runways (ashphalt or concrete)
2	Capable of VFR and IFR flight with an autopilot
3	Capable of flight in known icing conditions
4	Meets applicabale certifcation rules in FAA 14 CFR Part 25
5	Engine/propulsion system assumptions documented with use of engine(s) in service by 2029
Mission	
RBS	**Requirement**
1	Crew: 2 pilots, 8 flight attendants
2	400 passengers in a dual class configuration
2.1	50 Business class passengers with 36" seat pitch, 21" seat width
2.2	350 Economy class passengers with 32" seat pitch, 18" seat width
3	5 cubic feet per passenger for baggage
4	Galleys, Lavatories, and Exits to meet 14 CFR Part 25
5	Number of aisles appropriate to the passenger layout
6	Passenger/pilot/attendant weight of 200 lb
6.1	Baggage weight per occupant of 30 lb
7	3,500 nmi design range mission with reserve energy to meet 14 CFR Part 25 requirements
8	Maximum takeoff length of 9,000' over a 35' obstacle to a runway with dry pavement (sea level ISA + 15 °C) at MTOW
9	Maximum Landing field length of 9,000' to a runway with dry pavement (sea level ISA + 15 °C) at the end of design range mission
10	Maximum Approach Speed of 145 KCAS at the end of design range mission
11	Cabin pressurized to 8,000 ft pressure altitude at maximum flight altitude

Table 1.1: AIAA RFP Requirements

Chapter 2: Market Studies

Regional air travel has not always been confined to 150-seat, smaller aircraft. The problem with airport congestion is a new one, but aircraft capacity's role in the issue is an interesting story of air travel coming full circle. In past decades, airlines did in fact utilize widebody higher-capacity aircraft for shorter trips. Coast-to-coast or shorter hops like trips from Boston to Detroit were taken on 250-300 seater DC-10s, L-1011s or 747s. The first Airbus, the A300, was a widebody plane designed specifically for short and medium-haul routes. The A300 as operated by Eastern actually used to shuttle 250 passengers on half hour flights between Boston, New York and Washington [1].

So why did the airline industry adopt an approach that turned away from this model into one that offers smaller aircraft more frequently? There are numerous reasons. Technological advancement has allowed smaller jets with limited capacity to be profitable, which was not possible during the prime of the A300. Additionally, the Airline industry has expanded and the number of players in the game is substantially higher now than at any time in the past, providing customers with a greater number of options to get from point A to B. Finally, the biggest factor that led to the phasing out of higher capacity aircraft for short hops was the use of frequency as a selling point. Having 6 flights daily between Atlanta and New York on a single airline allows customers greater flexibility to travel according to their schedule instead of the airline's.

Airlines use a metric called breakeven load factor to determine what percentage of a plane must be occupied to cover their costs. Perhaps one of the most compelling reasons airlines currently utilize the smaller aircraft is because they are easier to fill and this allows them to hit or exceed their breakeven load factor more reliably [2]. In 2018, the average airline load factor hit a high of 81.7% indicating that airliners across the board were on average 81.7% full. *Figure 2.1* below shows load factor vs their break-even load factor for various airlines below. The greater the difference between these two numbers the more profitable the airline.

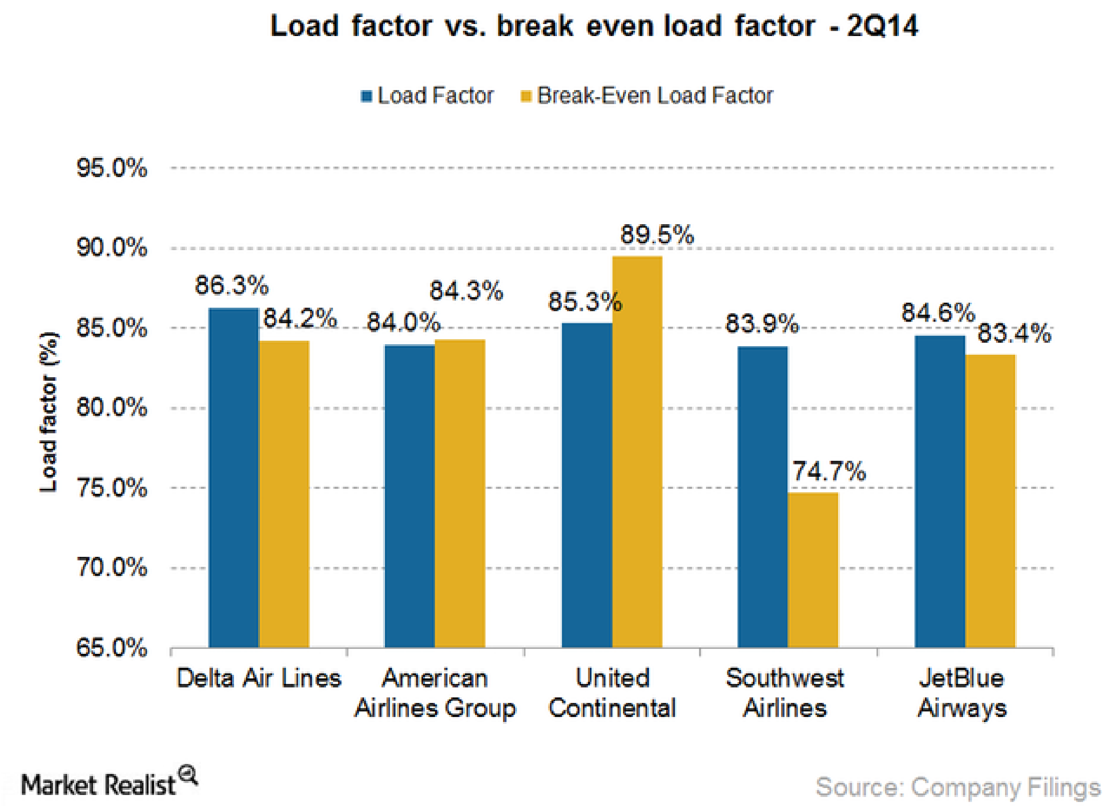

Figure 2.1: Load Factor vs. Break Even Load Factor Bar Chart [27]

Due to the ease of filling smaller planes and improving aircraft efficiency that allows the smaller aircraft to be profitable, congestion at major airports is at an all time high. Congestion will continue to get worse unless airport infrastructure, including runways and aircraft gates, is expanded in order to accommodate more takeoffs and landings. Alternatively, airlines could increase the capacity of their aircraft in order to decrease the frequency of takeoffs and landings. In fact, according to Boeing's latest market forecast, traffic on intra-regional routes will more than double between 2016 and 2036 and account for almost half the growth globally over the period [3].

Interestingly, this problem is more common in the US and Europe while Asian and Middle Eastern airline operators frequently operate larger aircraft on shorter routes. Emirates actually flies many of its 615 passenger A380s on high-density routes around the Middle East like their 1000 mile flight between Dubai, United Arab Emirates and Jeddah, Saudi Arabia. [21] This model may need to be readopted by Western Countries as the market for air travel continues to grow alongside airport congestion.

In Australia, Qantas Airways is seeking to solve that exact problem. At Sydney Airport, a flight takes off for Melbourne about every 10 minutes. Quantas mostly serves the Sydney-Melbourne-Brisbane triangle with Boeing 737s that carry 174 passengers. To replace that with a plane capable of carrying 240 people would shift the same number of passengers down to 73 percent of the landing slots. To replace that with a 400 passenger plane would further reduce that to less than 50% of the landing slots allowing for greater on-time reliability as a result of reduced congestion [3]. While there are already existing high density aircraft such as the A380, they are designed for long range flights of 6,000+ nmi and are not optimized for the short range missions which leaves an opening for a new, short range optimized design.

Chapter 3: Initial Design

Minimum Success Criteria

We must minimize operating cost of the aircraft based on a reference mission of 700 nm. Operating cost should include at a minimum: Fuel/energy cost, other consumables (oil, tires, etc), pilot and flight attendant cost, and maintenance cost**.** We also must demonstrate reliability equal or better than that of comparable aircraft**,** maintenance costs equal or better than that of comparable aircraft, and an aircraft purchase price competitive with comparable aircraft while using industry standard profitability models.

Verification Approach

Using existing fuselage, airfoil, and engine data, verification will be meeting required aerodynamic criteria while simultaneously improving some flight characteristics (fuel efficiency, flight time, thrust to weight, etc) relating to flights of 700 nm compared to current airliner offerings. If time allows, once an initial CAD model and CFD analysis completed, the model and simulation data will be transferred to a flight simulator in order to test flight characteristics

Problem Solving Approach

The first step to solving the challenge of efficient high capacity short range transport was to document and understand the metrics and tradeoffs involved with improving aircraft efficiency. We approached this problem from both an aerodynamic and propulsive perspective alongside a flight economics standpoint, because of the multiple dimensions of efficiency in play.

Methods of Improving Aircraft Efficiency

- TSFC
- Thrust/Weight
- Propulsive Efficiency
- L/D Ratio
- Wing/airfoil optimization for the given mission

Methods of Improving Flight Economics

Increased Cargo

One of the methods we are researching into improving the overall economics of flight is by way of increasing the cargo carrying capacity of our short range transport plane. In 2017, $11.9 billion in cargo revenues were generated via cargo in passenger planes in aircraft cargo holds representing 12% of all air cargo transport revenues [4]. Utilizing a larger, wide bodied aircraft with a maximum range of 3,500 nm that will be optimized to serve 700 nm flights for 400 passengers, the potential for cargo revenue could help offset some costs required by the necessary thrust and fuel requirements of a larger aircraft for these shorter flights. Specifically when dealing with major hubs, the demand for cargo transportation will grow faster than the demand for passenger flights with the rapid growth of e-commerce.

Decreased cost per hour/Passenger

A secondary aspect we have sought to benefit from as a product of utilizing higher passenger aircraft is a lower cost per hour/passenger. With the greater the number of passengers, we believe we can significantly reduce the costs per passenger per hour over existing smaller aircraft with substantially more engine cycles and takeoffs and landings. This will be proven through reducing the fuel, staffing, and maintenance requirements as well as airport landing and gate fees and dividing them amongst the number of passengers. We believe that our break even load factor can be reduced beyond what is currently capable amongst aircraft currently operating in our target range of 700 nm by optimizing the aircraft for said mission.

Chapter 4: Initial Sizing

4.1 Initial Weight Estimation

With the requirements for the transport aircraft specified, the initial weight estimation technique from [5] was utilized to get a first estimation of the aircraft's gross weight. The design variables that had to be chosen were the wing aspect ratio in order to determine the lift to drag ratio and the cruise speed. Existing aircraft were used as reference in order to make the required initial design choices.

The Boeing 757, 767, 777, and 787 were used as benchmarks to base our aircraft's wing aspect ratio and design cruise speed. The aspect ratios of the reference aircraft were between 8 and 10.6 [6], with the more modern 787 utilizing the highest wing aspect ratio of 10.6 which it is able to achieve thanks to the added strength of the composite wing structure [7]. The high aspect ratio of the modern 787 points to a new design trend of increasing wing aspect ratio, so a middle ground number of 9 was selected for initial weight estimation. The newer long haul Boeing 777 and 787 cruise at close to or at Mach 0.85 while the older short haul Boeing 757 and 717 cruise at mach numbers between 0.77 and 0.80 [8], [9], [10]. A design cruise speed of 0.85 mach was selected to match the more modern aircraft.

Using the design choices and the initial weight estimation techniques from [5], the calculated gross weight rounded to the nearest hundred pound was found to be 405,100 lbs. A trade study was then conducted in order to figure out the weight savings of composite construction. Using Raymer's composite construction fudge factor of multiplying 0.95 times the calculated empty weight fraction, a result of a gross weight of 370,200 lbs was obtained which is a 9% reduction in gross weight. The results of the trade study can be seen in *Table 4.1* below.

Table 4.1: Standard vs Composite Construction Trade Study

Initial Weights Trade Study	
Structure Type	**Gross Takeoff Weight**
Standard Construction	405,100 lbs
Composite Construction	370,200 lbs

4.2 Thrust-to-Weight Ratio and Wing Loading

In order to determine the thrust-to-weight ratio (T/W) and subsequently the wing loading (W/S) of our aircraft we consulted the techniques found in [5]. We utilized the statistical and "Thrust Matching" techniques in order to determine a baseline T/W requirement. The statistical method yielded a higher required T/W value that was somewhat greater than other existing aircraft such as the Boeing 787-10 [8] while the "Thrust Matching" method resulted in a value marginally lower than the B787-10. The higher value of 0.252 from the statistical method was chosen as recommended by Raymer. With a T/W value selected, a W/S value could be determined using Raymer's equations for different flight conditions. The results of the solved equations can be found in *Table 4.2*.

Table 4.2: Required Wing Loadings for Differing Flight Conditions

Flight Condition	Wing Loading (lb/ft^2)
Stall	100.24
Takeoff	127.00
Landing	131.68

The requirements from *Table 1.1* were used to determine the values for the variables in the equations. For the stall condition, a stall speed of 111 knots was selected as the requirements state an approach speed of 145 knots. FAR 25 requires that the approach speed to be 1.3 times the stall speed [5], which resulted in a stall speed of 111 knots. The stall condition provided the lowest required wing loading of 100.24 lb/ft^2, which is reasonable but marginally low when compared to other widebody aircraft. The Boeing 787-10 and 767-400 have takeoff wing loadings between 138 and 144 lb/ft^2 [8], [11]. The maximum coefficient of lift may need to be increased using a more advanced flap system in order to increase the wing loading for increased cruise efficiency. With that in mind, a design lift coefficient of 105 lb/ft^2 was selected. However, due to the short amount of time spent at cruise in the 700 nmi mission, the lower wing loading could prove to be beneficial in the climb and descent regions of flight.

4.3 Initial Wing Geometry

With the required wing loading calculated, the initial wing geometry was designed using equations from [5] which can be seen in *Appendix I*. Using the preliminary gross weight as calculated in section 4.1 and the required wing loading found in section 4.2, the reference wing area was found by dividing the gross weight by the wing loading. With the reference wing area found, the wing span was calculated using the aspect ratio selected in section 4.1. The rest of the initial wing geometry was selected by either referencing historical airliner wing geometry values as well as values suggested by Raymer in [5]. For example, the typical historical value for the wing dihedral on Boeing transport aircraft is 6 degrees [12], Raymer in [5] suggests a value of 3 to 7 degrees for a low, swept subsonic wing. An initial dihedral angle of 4 degrees was chosen for our aircraft due to the composite wings which will flex more in flight, requiring less static dihedral angle than conventional wings. The remaining wing geometry values can be found in *Table 4.3*

Table 4.3: Initial Wing Geometry Values

Wing Parameter	Value
Aspect Ratio	9
S (Reference Wing Area)	3,526 ft^2
Wing Span	179 ft
Wing Incidence	~1°
Dihedral Angle	4°
Wing Sweep	32°
Taper Ratio	0.2
C_{root} (Root Chord)	32.83 ft
C_{tip} (Tip Chord)	6.566 ft
$\bar{c}$ (Mean Aerodynamic Chord)	22.6 ft
$\bar{Y}$ (MAC Distance)	34.8 ft

At this stage of the design, we have selected the NASA SC(2)-0714 supercritical airfoil as our candidate airfoil. Utilizing a modern supercritical airfoil was necessary due to the high subsonic cruise speed that we are targeting. A supercritical airfoil is "characterized by a large leading-edge radius, reduced curvature over the middle region of the upper surface, and substantial aft camber" [13].

These qualities make the supercritical airfoil well suited to high subsonic speeds where airflow along the upper surface of the wing may be traveling at speeds above Mach 1. When approaching the speed at which supersonic flow first appears on the upper wing surface, known as "critical Mach", shocks will form on the wing, causing boundary layer thickening and eventually separation, resulting in a sharp increase in drag. The flatter upper surface of the supercritical airfoil reduces the intensity of the shock, delaying the onset of boundary layer separation and increasing the critical Mach number [5], [13].

While the Supercritical airfoils allow for an increase in high subsonic cruise through an increase in critical Mach number, they do not sacrifice low speed and transient performance or stability [13]. The selected supercritical airfoil has a maximum thickness to chord ratio of 14%, as seen in *Figure 4.1* which should provide ample coefficients of lift at high angles of attack in order to satisfy the takeoff, climb, and landing requirements. Airfoil data for modern airliners to use as reference is difficult to come by as most airliners use application unique airfoils which are held as trade secrets, however, limited data for the Boeing 767 is available. The Boeing 767 variants are known to use a proprietary supercritical airfoil with a maximum thickness to chord ratio of 15.1% at the root and 10.3% at the tip [14]. This indicates that a 14% ratio should be a good starting point and that it may be worthwhile to experiment with a thinner supercritical airfoil at the tip of the wing.

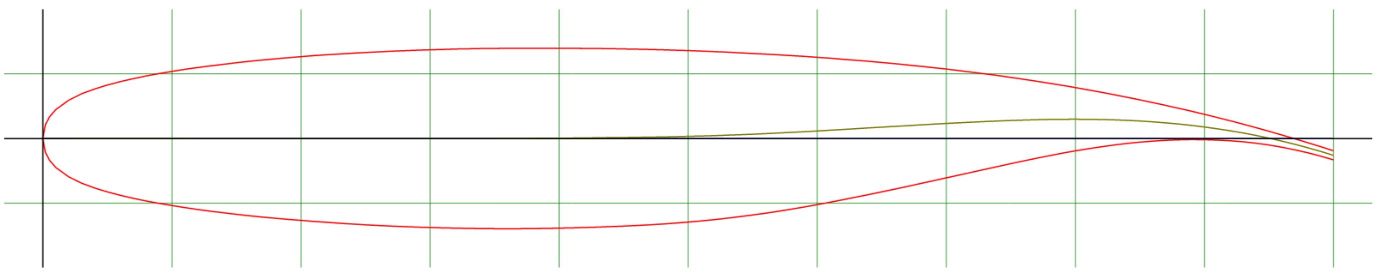

Figure 4.1: NASA SC(2)-0714 AIRFOIL [15]

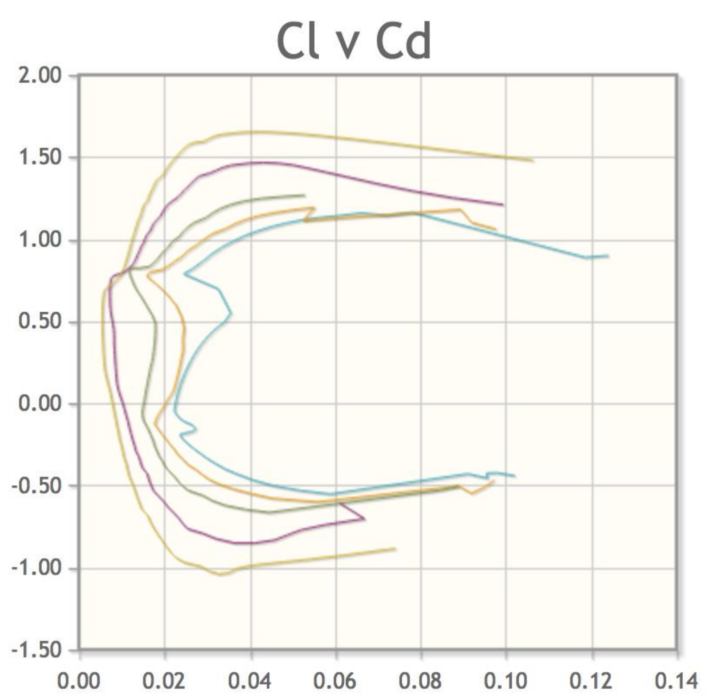

Figure 4.2: Drag Polar Diagram of the NASA SC(2)-0714 Airfoil [15]

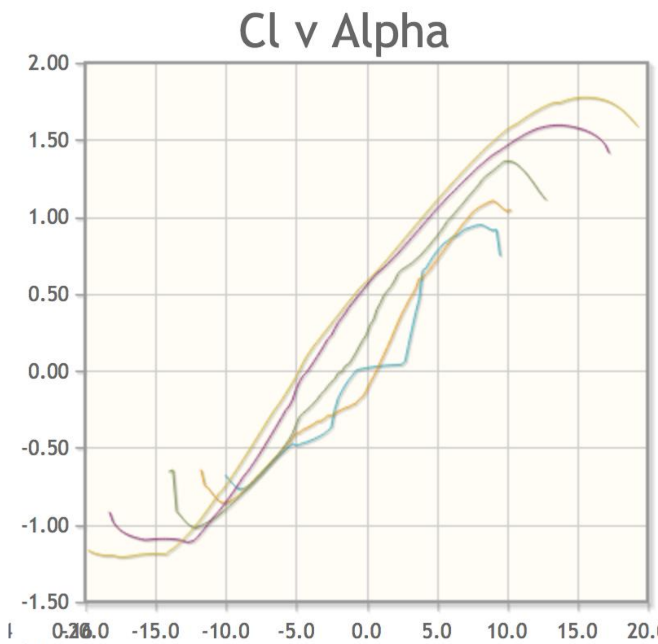

Figure 4.3: Lift vs. Angle of Attack Diagram for the NASA SC(2)-0714 Airfoil [15]

4.4 Revised Weights

With the initial wing geometry selected, an improved method of weight estimation equations from [5] were utilized in order to provide a more accurate initial weight estimate. The spreadsheet used for these calculations can be found in *Appendix II*. This method is more accurate in numerous ways, including taking into account the fuel burned at each mission segment and taking that weight loss into account for the fuel burn of the next mission segment. The weight results from using the method as provided in section 6.3 of [5] are listed in *Table 4.4*, and resulted in a gross weight estimation that was 16.1% greater than the initial weight estimation.

However, when comparing the new weight results to the Boeing 787-8, the new result seems reasonable. The B787-10 has a range of 6,430 nmi, 1.84 times greater than the SB-400's design range and a fuel weight of 248,866 lbs which is 1.96 times greater than the SB-400's calculated fuel weight. Both values are nearly two times that of the SB-400's range and fuel weight, which makes for a reasonable assumption that a modern composite aircraft with twice the range of the SB-400 would require twice the fuel capacity.

Table 4.4: Revised Initial Weights

Revised Weights	
Fuel Weight	127,054 lb
Empty Weight	213,572 lb
Gross Weight	434,927 lb

4.5 Revised Wing Geometry

With the large increase in weight incurred after revising the weight estimate, the wing geometry needed to be revised in order to meet the target wing loading. With a higher wing area required in order to achieve the target wing loading, the wingspan and/or wing chord had to be increased. At this point, it was decided that the aspect ratio could be increased to 10 in order to further increase SB-400's aerodynamic efficiency and more closely match the higher aspect ratios of modern airliners. The only consideration towards limiting the aspect ratio is the wing span and the logistical consequences of a large wing span.

Most all major airports are capable of handling Group V aircraft, or aircraft with a wingspan up to but not including 214 ft. Aircraft with a wingspan of 214 ft up to but not including 262 ft are considered Group VI aircraft consisting of only two aircraft, the Boeing 747-8 and Airbus A380 [15], [16]. Group VI equipped airports are limited, as are the gates actually equipped to handle Group VI aircraft at those airports. Therefore, it's important that the SB-400's span be kept well under the Group VI threshold for ease of movement around the airport as well as plenty of compatible gates. The revised wing geometry can be found in *Table 4.5*.

Table 4.5: Revised Initial Wing Geometry

Wing Parameter	Value
Aspect Ratio	10
S (Reference Wing Area)	4142 ft^2
Wing Span	203.5
Wing Incidence	~1°
Dihedral Angle	4°
Wing Sweep	32°
Taper Ratio	0.2
C_{root} (Root Chord)	33.92 ft
C_{tip} (Tip Chord)	6.78 ft
$\bar{c}$ (Mean Aerodynamic Chord)	23.37 ft
$\bar{Y}$ (MAC Distance)	39.57 ft

4.6 Initial Tail Surface Sizing

With the revised initial wing geometry completed and the length of fuselage known from the layout completed in section 6.3, the tail surface areas could be calculated. The tail surface areas were calculated using equations from [5] involving an estimated required tail moment arm based upon the fuselage length. The results of the equations can be seen in *Table 4.6* below.

Table 4.6: Values for the Initial Tail Surface Sizing

Initial Tail Surface Sizing	
Tail Surface	**Area**
Horizontal	870 ft^2
Vertical	682 ft^2

The dimensions specified as results of the revised wing and tail geometry can be seen in a final CAD drawing in *Figure 4.4*.

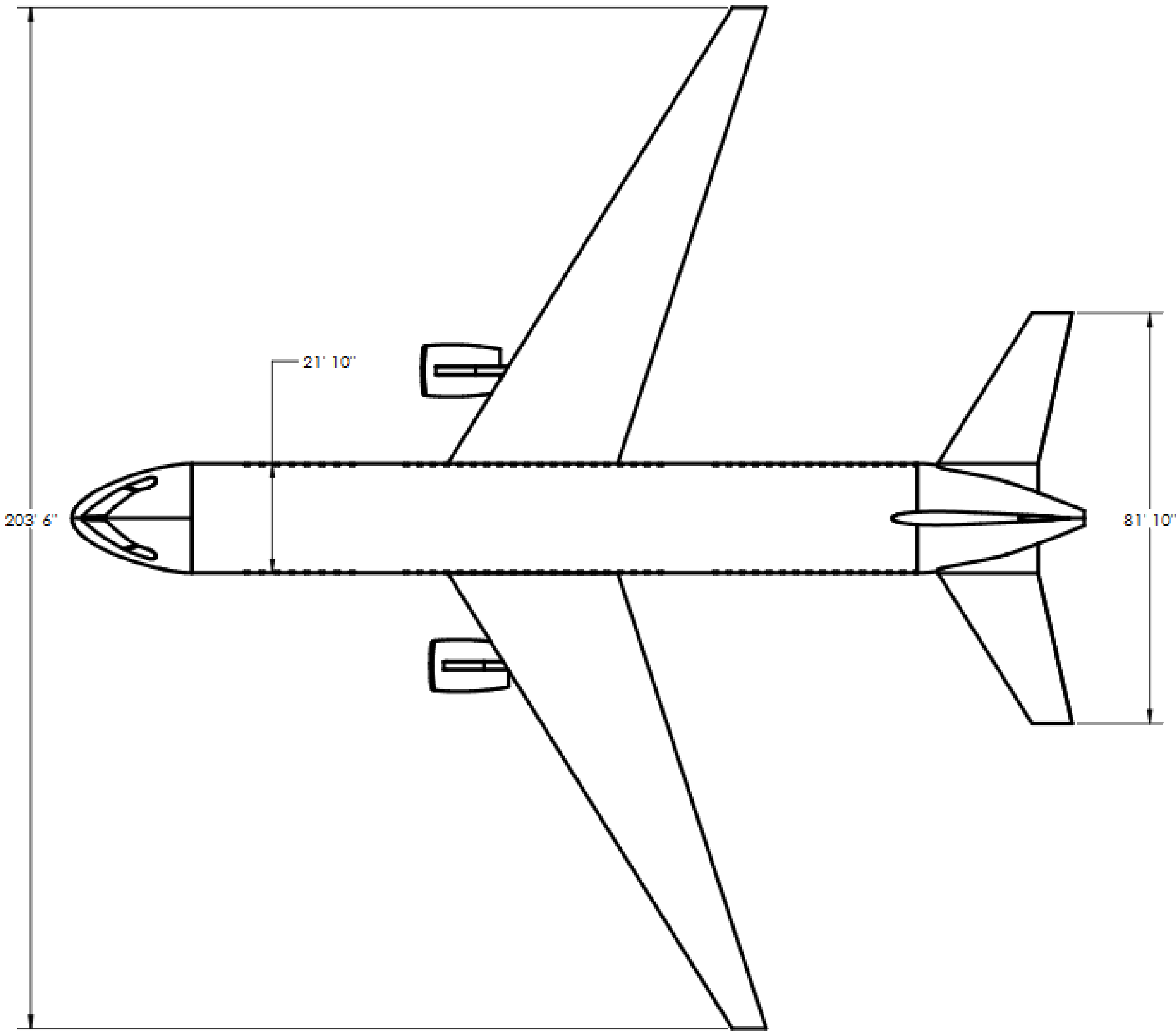

Figure 4.4: SB-400 CAD Top View Drawing

Chapter 5: Aircraft Configurations

5.1 Fuselage Configurations

The main requirement for the fuselage is to accommodate the RFP's requirement for 50 business class seats, 350 economy seats as well as enough galleys, lavatories, and exits that meet 14 CFR Part 25 requirements. The fuselage will need to have a minimum of two doors, but will have more due to exit requirements for such a high passenger capacity aircraft. At least two cargo doors beneath the passenger compartment will be necessary in order to load and unload cargo and luggage from the cargo hold. The seating arrangement in regards to seat per-row is to be determined by fuselage width to length ratios, or the fineness ratio, but it is known that at least two separate isles will be required based upon historical reference aircraft. In regards to fuselage shape, the traditional cigar shape as found on other airliners is known to be the most ideal shape for the fuselage due to ease of construction and efficiency.

5.2 Wing Configurations

Most historical reference airliners utilize a low wing design. Other options including high-wing, and even delta-wing configurations were considered. A delta wing design was considered for a very high subsonic speed airliner, cruising somewhere around Mach .95-.98, but it was decided that so little time is spent at cruise for the desired 700 nmi mission that the initial purchase and operating expenses of such a complex aircraft could not be justified. The high-wing configuration had the added benefits of easier loading and unloading of cargo and passengers as well as being able to fit large diameter turbofans without a tall landing gear which reduces landing gear weight. However, the trade-offs were numerous. The engines next to the fuselage would cause increased cabin noise, the required T-Tail would complicate tail maintenance and add increased mechanical complexity and weight, landing gear placement would involve compromises, and the overall weight of the design would likely be higher. In the end, the conventional low wing design was selected.

5.3 Tail Configurations

The selection of the tail configuration for the SB-400 was straightforward. Without a high wing design or plans for rear mounted engines, the added weight and complexity of a T-Tail was unnecessary. T-Tails also have a tendency to suffer from deep stalls, a situation where the elevator control surface on the T-Tail is blanketed by the wake from the wing when in a stall at an extremely high angle of attack, causing an unrecoverable stall. Because of those factors a tried and true conventional tail, with a horizontal stabilizer located low on the empennage and a separate vertical stabilizer, was selected.

Chapter 6: Passenger Compartment Layout

6.1 Seats

The first step we took to design the plane was defining our passenger seating and seat layout. From the seat requirements defined by the proposal, a seat was designed for both the economy and business class sections. The seats were placed in various configurations to determine the best passenger compartment layout.

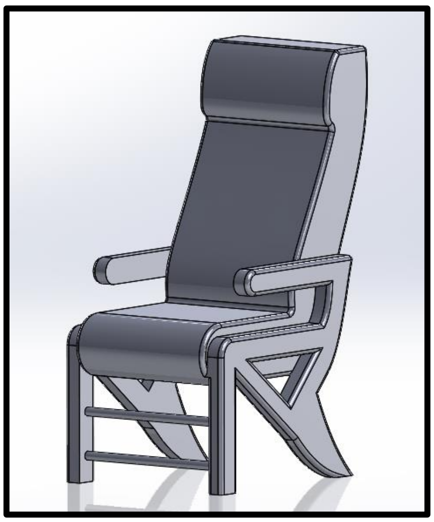

Figure 6.1: Initial Seat Design

The Business class seats are 21 inches wide with a 36 inch pitch. The seats are 52 inches tall to accommodate the 95th percentile of the American population(1). The arm reset are 3 inches wide to add to the ‘luxury’ of Business class when compared to Economy. The storage available underneath each Business class seat is 21 inches wide by 12 inches tall by 22 inches deep to make 3.2 cubic feet of individual passenger cargo space. The economy seat has a pitch of 32 inches, a seat width of 18 inches, and a height of 48 inches. The armrests are 2 inches wide and the storage beneath each seat is 18 inches wide by 12 inches tall by 20 inches deep to make 2.5 cubic feet of personal cargo space, half of the overall requirement per passenger.

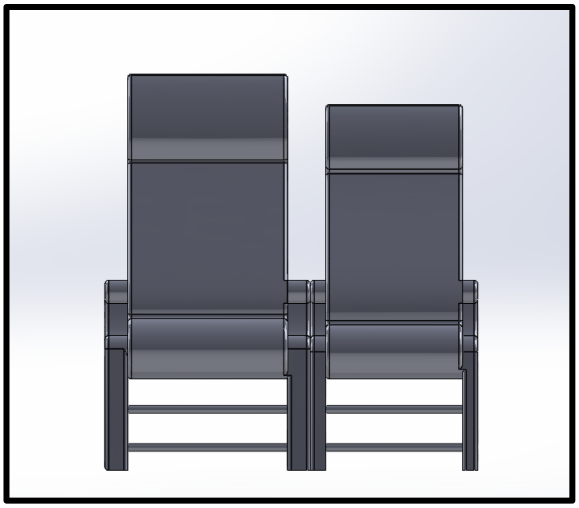

Figure 6.2: Business and Economy Seat Comparison

6.2 Seat Layout

From the seat design, a preliminary floor layout can be created. Multiple seat configurations were designed to get an idea of the best floor plan. To fit the required seats in the fuselage, a 3-4-3 row layout was created for the Economy class in combination with a 3-3-3 row layout for the Business class. This layout seats 350 passengers in Economy class and 54 passengers in Business class. Though this initial layout does not account for necessary emergency exit doorways and proper galley areas, the layout allows us to get an idea of the required fuselage length and diameter for initial sizing.

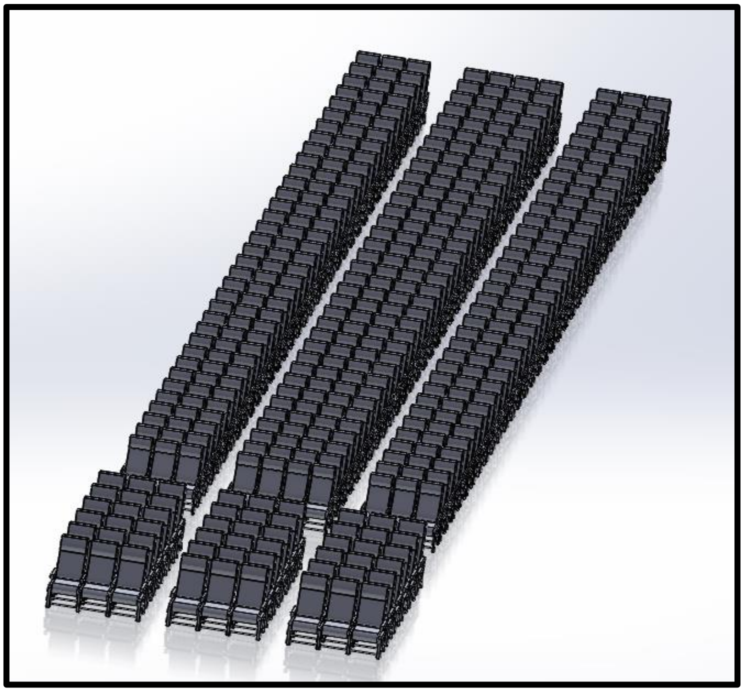

Figure 6.3: Preliminary Seat layout

6.3 Fuselage Design

With the business and economy class seats designed to meet the specifications set forth, the design of the fuselage can be created from the inside, out. The fineness ratio refers to the ratio of an aircraft's fuselage length to its diameter. Using the seats that have been designed we can determine the aircrafts inner diameter then find the overall fuselage length or that given diameter. Comparing the length the fineness ratio determines will ultimately help determine the seat layout within the cabin.

The outermost passenger in a row of seats must have a radius of 10 inches of head space from where their eyes are. For an average sitting passenger their eyes, when accounting for seat width and armrest width, is located 11 inches from the outermost part of the row and 48.5 inches from the ground.

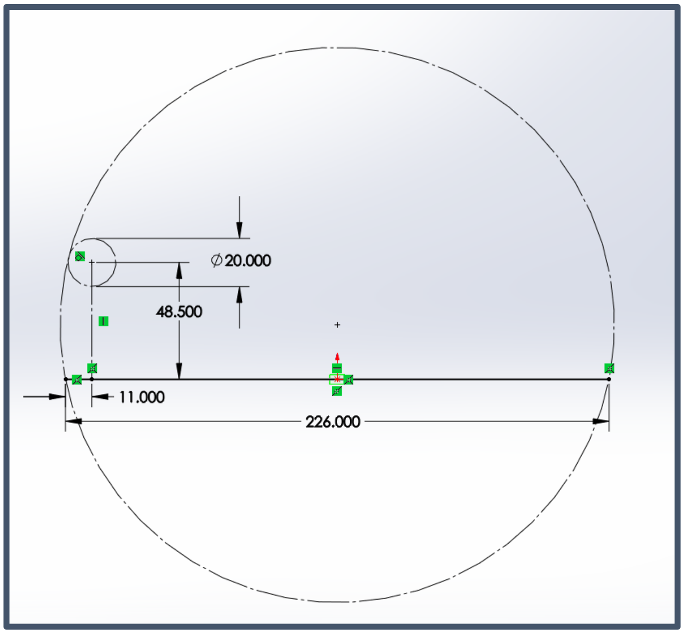

Figure 6.4: Dimensions for 3 by 3 Seat Configuration with a Single Aisle

A 3-3, 2-3-2, 3-3-3, and 3-4-3 seat configurations were designed and the minimum possible floor spans for the restrictions we have set in place can be seen in *Table 6.1*.

Table 6.1: Seat Configurations and Respective Fuselage Dimensions

Seat Configuration	Floor Width	Inner Diameter
3-3	144 in	151.65 in
2-3-2	186 in	191.67 in
3-3-3	226 in	230.48 in
3-4-3	246 in	250.03 in

An additional six inches is added on to account for structural thickness differences between the outer and inner diameter [5]. This outer diameter for each seat configuration can then be used to determine the respective fuselage length. For nearly all subsonic aircraft, the fineness ratio falls between 6-8 [5]. We will assume a fineness ratio of 7 for our rough length approximations. With all the outer diameters determined, the fuselage length for each seat layout is determined.

Table 6.2: Seat configurations and their respective required fuselage sizes.

Seat Configuration	Outer Diameter	Fuselage Length
3-3	157.65 in (13.14 ft)	1103.52 in (91.96 ft)
2-3-2	197.67 in (16.47 ft)	1383.68 in (115.31 ft)
3-3-3	236.48 in (19.71 ft)	1655.33 in (137.94 ft)
3-4-3	256.03 in (21.34 ft)	1792.19 in (149.35 ft)

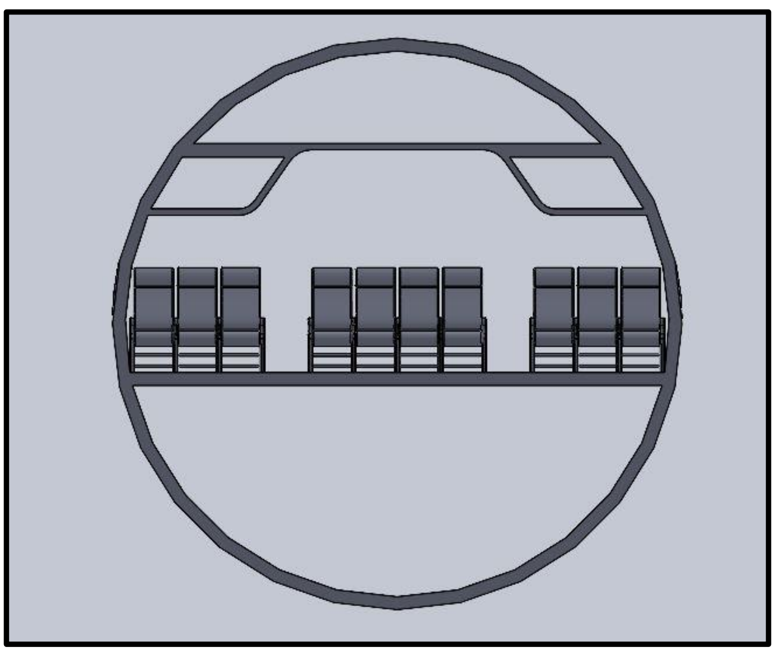

Figure 6.5: Fuselage Cross Section in Economy Class

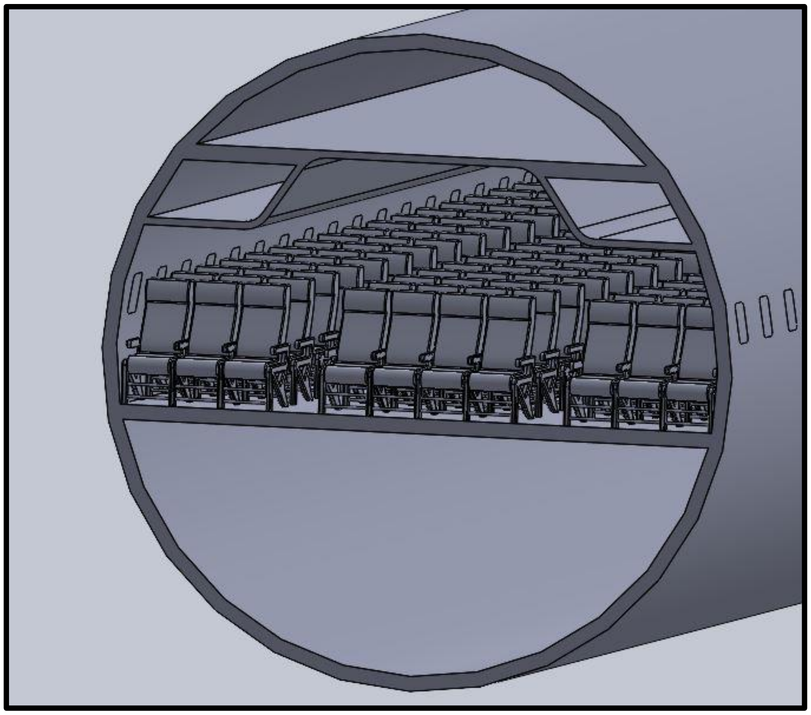

Figure 6.6: Isometric View of Fuselage Cross Section

The completed fuselage assembly can be found in *Figure 6.7*. With the addition of the nose/cockpit, the empennage section, the required emergency exits and galley areas, and the selected 3-4-3 seat layout for economy class the total length of the fuselage came out to be 201' and 11".

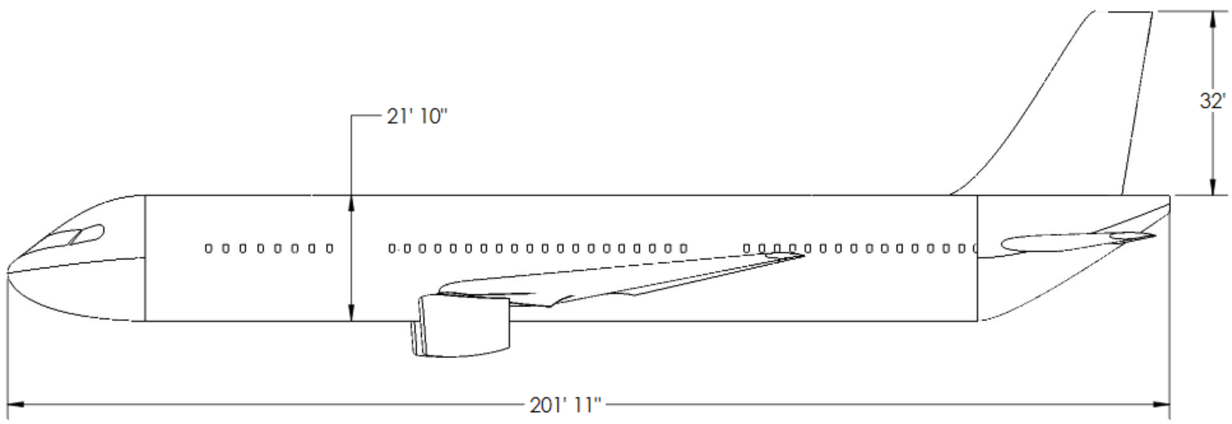

Figure 6.7: SB-400 Side View Drawing

Chapter 7: Design Procedure

7.1 Wing Layout

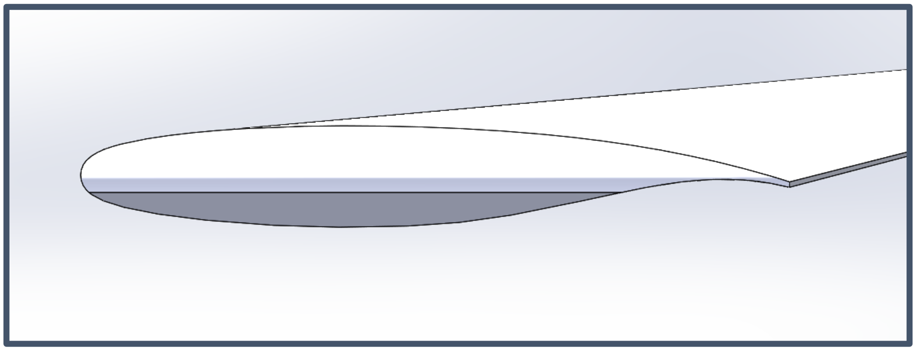

Figure 7.1: Section View of the Wing with the NASA SC(2)-0714 airfoil

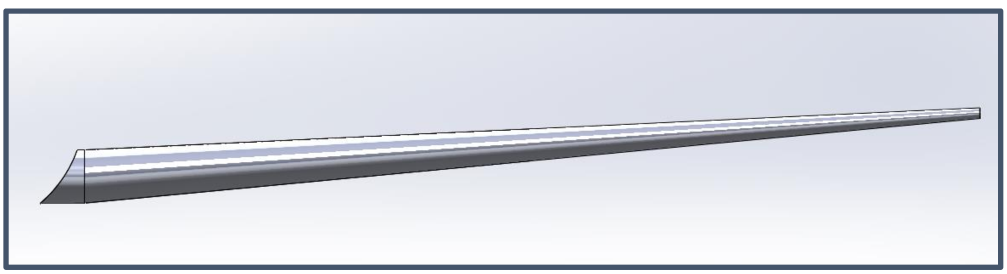

Figure 7.2: Front View of the Wing

Chapter 8: Engine Selection

The new jet age will be one not marked by high performance afterburning engines and aircraft more capable than the humans that fly them; rather, the new jet age is an efficiency driven one that will see engines with ultra-high bypass ratios, geared turbofans, and materials capable of withstanding temperatures unheard of. Our engine selection for the SB-400 required an initial determination of required thrust. We utilized both the statistical method and the “Thrust Matching” method and determined our optimal thrust/weight value will be 0.252. We previously determined our empty weight to be 213,572 lb or 106,786 kgs. Using this we determined that we needed engines that could produce at least 211.88 kN or 47,630 lbf of thrust, more once we determined cargo, fuel, passenger and baggage weight. For similarly sized aircraft, we determined that most aircraft had a maximum takeoff weight greater than double their empty weight. selected five engines that produce between 327kN or 73,000lbfs and 419kN or 95,000lbfs of thrust and are currently in operation or have been tested for future use.

Baseline Engine: Pratt Whitney PW4052

We decided to use the Pratt Whitney PW4052 as our baseline engine because it produces thrust in excess of our needs for an empty aircraft with 52,000 lbf or 231.3 kN and it has one of the most efficient engines currently in operation with a stated TSFC of 0.312 or 8.834 g/s*kN. [28] The PW4052 is currently utilized on the 767-200ER/-300ER.

Baseline Fuel Burn

One of the current aircraft we have designed our Skybus SB-400 around is the 777-300 due to its similar passenger capacity and widespread use. In order to improve the economics of flight in this size aircraft, we used the fuel burn at cruise for a 777-300 ER which is estimated at 7.5 tons/hour. [30] This equates to a fuel burn of 15,000lbs/hr as our benchmark value to beat. We also believe we can beat the economics per passenger of an aircraft typically used in 700nm flights, the 737-800.

Engine Summary

We The five engines and performance data can be seen in *Table 8.1* below. Baseline Output, Pressure ratios, BPR, and fuel flow data was obtained from the ICAO databank [28] at different flight conditions.

Table 8.1: Candidate Engine Performance Data

	Trent 7000-72	Genx-1B76A/P2	Trent 1000-R3	GE90-90B	PW4084
BPR Takeoff	9	9.1	8.9	8.36	6.4
Pressure Ratio Takeoff	45.4	47.4	49.4	39.85	36.2
Rated Output Fmax (kN)	327.9	349.2	363.9	419.25	369.6
Rated Output Fmax (Lbm)	73,712	78,500	81,805	94,247	83,086
Takeoff Fuel Flow (100% Fmax) (kg/s)	2.478	2.79	2.783	3.38	3.411
Output (kN)	328	349	364	419	370
TSFC (g/(s*kN))	**7.56**	**7.99**	**7.65**	**8.06**	**9.23**
Climb Out Fuel Flow (85% Fmax) (kg/s)	2.029	2.262	2.266	2.735	2.689
Output (kN)	278.715	296.82	309.315	356.3625	314.16
TSFC (g/(s*kN))	**7.28**	**7.62**	**7.33**	**7.67**	**8.56**
Approach Fuel Flow (30% Fmax) (kg/s)	0.67	0.709	0.723	0.852	0.875
Output (kN)	98.37	104.76	109.17	125.775	110.88
TSFC (g/(s*kN))	**6.81**	**6.77**	**6.62**	**6.77**	**7.89**
Idle Fuel Flow (7% Fmax) (kg/s)	0.241	0.223	0.262	0.28	0.242
Output (kN)	22.953	24.444	25.473	29.3475	25.872
TSFC (g/(s*kN))	**10.50**	**9.12**	**10.29**	**9.54**	**9.35**

The data can be seen to indicate that the four engines all have similar thrust specific fuel consumption rates and the rated output thrust is also close amongst all engines. In looking for a dual engine setup capable of producing more than 600kN of thrust, all meet the minimum requirements but not all are equally suited to our mission. In *Table 8.2* below, it can be seen that the lowest fuel per passenger per hour is for the baseline engines; however, the baseline engines do not have adequate thrust for our purposes, lacking our minimum threshold by approx 140kN. Therefore, the engine with the minimum fuel per passenger per hour that meets all requirements is the Trent 7000-72.

Table 8.2: Comparison of Engine Parameters

	Trent 7000-72	Genx-1B76A/P2	Trent 1000-R3	GE90-90B	PW4084	PW4052 - Baseline
Max Thrust (N)	655,800	698,400	727,800	838,500	739,200	462,600
Available Thrust (N)	2,602,381	2,771,429	2,888,095	3,327,381	2,933,333	1,835,714
Available Weight @ .252 T/W	1,555,878	1,724,926	1,841,592	2,280,878	1,886,830	789,211
TSFC @ Approach/Cruise (30% Fmax)	6.81	6.77	6.62	6.77	7.89	8.83
Fuel Burn both engines (kg/s)	1.34	1.42	1.45	1.70	1.75	1.23
Fuel Burn both engines (kg/h)	4,824	5,105	5,206	6,134	6,300	4,412
Fuel Burn both engines (lb/h)	10,637	11,256	11,478	13,526	13,892	9,727
Fuel per passenger per hour (lb/h)	26.59	28.14	28.70	33.82	34.73	24.32

The engine comparison by TSFC at cruise as well as maximum thrust can also be seen in *Figure 8.1* below.

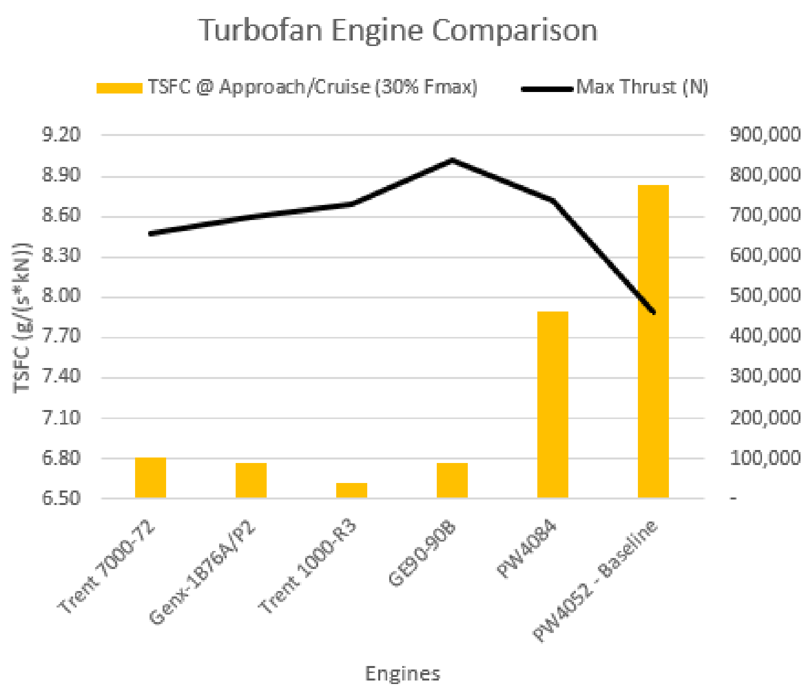

Figure 8.1: Candidate Engine Efficiencies in Cruise and Max Thrust

It should be noted that TSFC is lower than the values we would expect operationally. In a paper Titled Analysis of Aircraft Fuel Burn and Emissions in Landing and Take Off Cycle using Operational Data, Messrs. Chati and Balakrishnan detail the shortcomings of ICAO test methods, which are conducted at static sea level static ISA (SLS-ISA) conditions. Additionally the data collected is modeled only tor Landing and Takeoff cycles which represent only flight cycles that happen below 3,000 ft above ground level (AGL) ICAO's methodology assumes that irrespective of aircraft/engine type and the airport of operation, the takeoff roll occurs at a constant 100% thrust setting for 42 seconds, the climbout at a constant 85% thrust setting for 240s and the taxi/ground idle at a constant 7% thrust setting for 1560s. [31] The aforementioned paper utilizes data from flight data recorders (FDR) and adjusts them to equivalent SLS-ISA conditions and found that the ICAO databank is found to typically overestimate the mean times in various flight modes by as much as 52%, and typically underestimate the operational values of fuel flow rates.

Despite the shortcomings of the ICAO testing, the data provided is objective and represents performance data under near identical situations. This allows us to compare the data and make a determination of the best engine for our need and gauge a rough estimate of range and payload capacity.

Decision Making Process

To determine the best engine for our needs, we needed to also determine the economics and value of adding thrust in terms of cargo carrying capacity. In that sense, the two most important metrics for our determination were thrust as well as TSFC.

Engine Selection: Trent 7000-72

The Rolls-Royce Trent 7000 is designed as an exclusive engine for the Airbus A330neo family and borrows architecture from the Trent 1000 TEN – the latest version of the Trent 1000 Engine, technology from the Trent XWB – the world’s most efficient large civil engine, and the Trent 700 – the engine of choice for the current A330. The Trent 7000 reduces specific fuel consumption by 10% and has twice the bypass ratio as compared to the Trent 700 and also has a noise reduction of 6dB.

The Rolls-Royce Trent 7000 features a pressure ratio of up to 50, utilizes Advanced materials and ceramic coatings on High Pressure turbine blades that operate in temperatures of 1700C, and utilizes 24/7 engine health monitoring that relays performance information back to Rolls-Royce allowing for immediate analysis and maintenance planning. [23]

Based on ICAO testing, the engine has a rated output (Fmax) of 327.9 kN. For two engines, our thrust output is 655.8 kN. At cruise the engine burns 1.34 kg/s of fuel which equates to a fuel burn of 10,612 lbs/hr or 4824 kgs/hr. [28] When compared to the other engines as well as our baseline fuel consumption model, our engine has a TSFC that is 22.9% better than the PW4052 and a fuel consumption per passenger per hour that is 23% better than the 737-800 and 41% better than the 777-300ER.

As can be seen in *Table 8.3* below, the Trent 7000-72 as installed on the SB-400 has significantly reduced the cost per hour per passenger.

Table 8.3: Comparison data between the SB-400 with the Trent 7000 installed versus current airliner offerings.

	SkyBus	737-800	777-300ER
Capacity	400	162	368
Fuel Burn (lb/hr)	10,637	5,579	16,538
Fuel per Passenger per Hour (lbs)	26.59	34.44	50.11
Fuel cost per hour*	$7,978	$4,184	$12,403
Fuel Cost Per Passenger per hour	$20	$26	$34
Increased Cost over Skybus	-	23%	41%

Chapter 9: Costs and Economics

Current operating breakdown for US airlines is as follows:

- 44% is aircraft operating expense, which includes fuel, direct maintenance, depreciation, and crew
- 29% is servicing expense
    - Aircraft servicing (7%)
    - Traffic servicing (11%)
    - Passenger service (11%)
- 14% is reservations and sales expense
- 13% is overhead expense
    - Advertising and Publicity (2%)
    - General and Administrative (6%)

Our focus will be mostly on reducing aircraft operating expenses, however there will be additional savings in servicing expenses by virtue of reduced takeoffs and landings due to greater capacity. Our preliminary aircraft operating expenses as well as our targets for profitability optimized for 700 nm flights are indicated below:

- Typical aircraft used in 700 nm flights
    - Airbus A321
- Typical 700 nm flight ticket costs
    - ATL - NYC (~660 nm) $129-$169 economy
- Hourly plane cost
    - Airbus A321 (192 seats)
    - $3,970/hr
        - Fuel - $1,443

    - Aircrew - $570
    - Maintenance - $727
- Income per flight: $169/seat x 192 seats = $32,448
- Cost per flight: 2 hours x $3,970 = $7,940
- Profit per ticket: $127.64 [29]

We are seeking to produce equal or greater profit per ticket than is currently available via the Airbus A321 as well as substantially improved profitability over similar capacity aircraft on the same 700 nm flight.

One of the methods we are seeking to improve this is by increasing cargo hold capacity to tap into an underutilized market for passenger cargo hold transport. As e-commerce continues to grow, we believe that to fully utilize the unique mission of this plane in serving major regional hubs with a high capacity large body aircraft, we can offset and reduce the breakeven load factor on a per passenger basis by increasing cargo carrying capacity. This also provides us the ability to reach out and achieve the maximum range by reducing or eliminating extraneous non-passenger cargo, thus reducing the weight and increasing fuel economy.

The value of goods carried by airlines is expected to exceed $6.2 trillion in 2018, representing more than 35% of global trade by value [19]. This results in air cargo revenue in excess of $100 billion, as shown in *Figure 9.1* below.

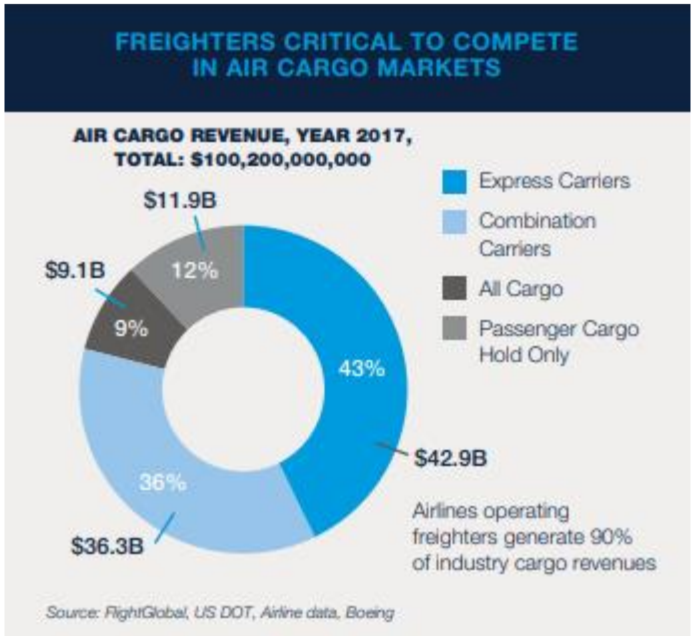

Figure 9.1: Air Cargo Trade Shares. [19]

To adequately portray the scale of the market and the growing trend, Boeing research indicates the following:

"Overall, North America air cargo traffic grew 4.2 percent in 2016 and 10 percent in 2017. US domestic air cargo, which accounts for 96.4 percent of the North America market, grew 4.2 percent in 2016 and 10.3 percent in 2017, while Canadian domestic air cargo, 2.2 percent of the market, grew 4.8 and 4 percent, respectively, over the same time period. For 2017, transborder traffic from the United States to Canada made up 1.2 percent of the North America market; traffic in the opposite direction made up 0.2 percent." [20]

Furthermore, Air Cargo World indicates:

"The number of airplanes in the worldwide freighter fleet will increase by more than 80 percent during the next 20 years, as demand for air cargo services nearly triples"[26]

Presently, only 30% of lower-hold capacity of new widebody aircraft has served primary cargo airport routes. [22] This is because the bulk of widebody aircraft serves international long distance travel and not the regional hub to hub transport sought for optimization by the SB-400. "The vast cargo capacity of today's large jets — the Boeing 777-300ER can carry more than 20 metric tons (44,000 lbs) in the holds in addition to a full load of 400 passengers — can make the difference between profit and loss on a route. On average, 50% or more of international flights are only profitable due to cargo's contribution" [25]. Based on sabre airlines solutions' pricing rates shown in *Figure 9.2* below, this translates to revenue of $30,000 per flight in cargo in addition to passenger revenue.

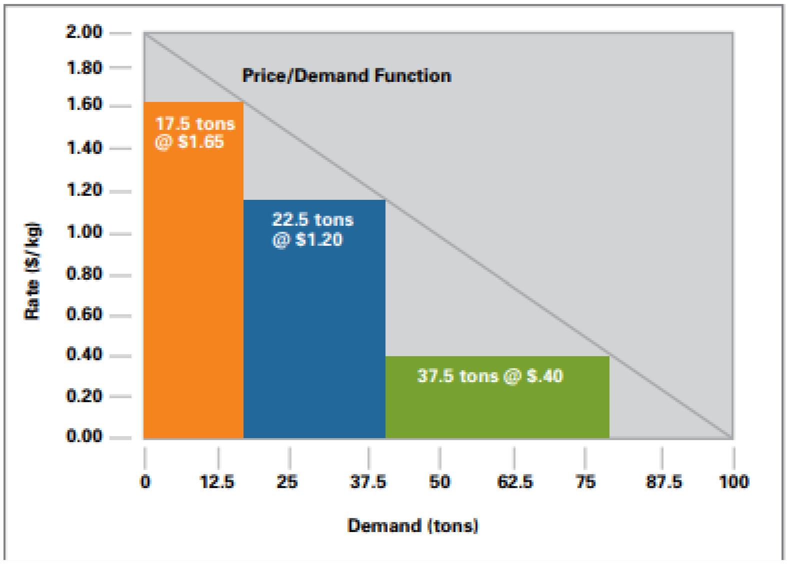

Figure 9.2: Rate for Cargo Transport vs. Demand [24]

The 777-300ER also has twice the range required by our aircraft and will primarily serve hubs that are 10% of the maximum range of the 777-300ER. By taking advantage of the lesser fuel requirements as well as the difference in typical passenger cargo requirements for an international flight versus a regional flight, we are seeking to significantly increase the cargo carrying capacity should the resulting math substantiate our belief that cargo can be a method for increasing revenue without sacrificing optimum loads on 700 nm flights.

Chapter 10: Final Design

Figure 10.1: SB-400 CAD Model Isometric View

Figure 10.2: SB-400 CAD Model Front View

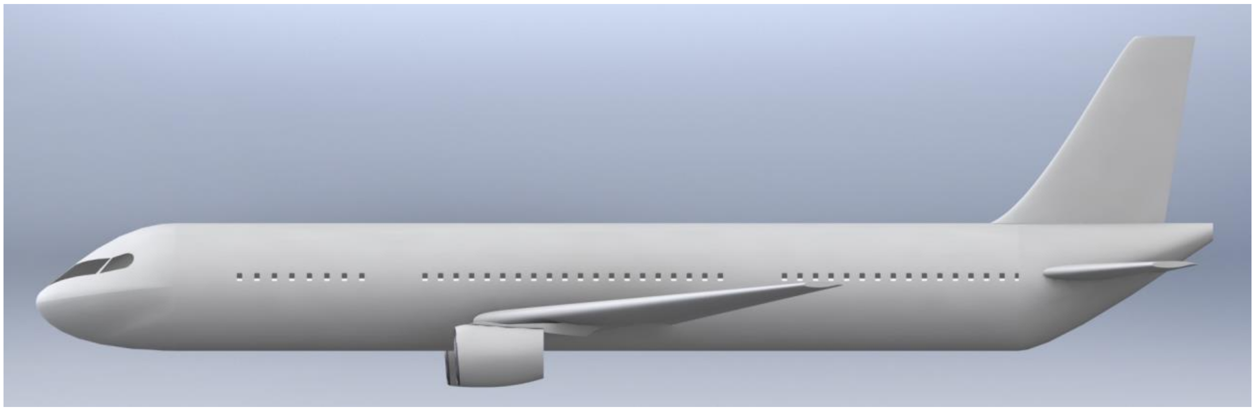

Figure 10.3: SB-400 CAD Model Side View

Figure 10.4: SB-400 CAD Model Top View

Chapter 11: Conclusion

In conclusion, we were able to meet or exceed most minimum requirements while simultaneously reducing the current cost per passenger on a 700 nm flight. Our carbon fiber material choice prevents corrosion that can occur on aluminum aircraft, reducing maintenance, as well as increasing the useful life cycle of the airframe all while reducing weight. The SkyBus can carry 400 passengers burning 10,600 lbs/hr of fuel resulting in a fuel per passenger per hour rate of 26.6 lbs/hr. As stated in Chapter 8, the SB-400 is more economical on 700 nm flights than existing airliners which currently fulfill those routes. With an economically advantageous design, airlines are more likely to show interest in the SB-400 which would lead to future success in sales. However, more design refinement and analysis would need to be done in order to meet all of the AIAA requirements. Therefore, a list of suggestions for future work has been placed below.

- Further fleshing out of interior systems and more thorough weights and balances analysis performed.
- Continued refinement of the main airfoil through CFD and flight sim analysis.
- Using simulation to confirm performance and stability of design.
- Continued wing and tail geometry iterations as the design develops with continued analysis.

Chapter 12: Appendices

12.1 Acknowledgments

Dr. Adeel Khalid: For his leadership and pioneering in KSU's Aerospace minor program as well as his continued support for students just like us in his Aerospace elective courses. Without him, this project would not have been possible.

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Ms. Christina Turner: For her role in keeping the Aerospace program running and her patience in assisting us with our poster.

Mr. Daniel Kuemmerle: For his assistance in solving iteration problems with Microsoft Excel.

12.2 Appendix I: Initial Wing Geometry Equations

(1) $$S = \frac{W_0}{(W/S)}$$

(2) $$b = \sqrt{A * S}$$

(3) $$C_{root} = \frac{2 * S}{b(1+\lambda)}$$

(4) $$C_{tip} = \lambda * C_{root}$$

(5) $$\underline{c} = \frac{(2/3) C_{root}(1+\lambda+\lambda^2)}{1+\lambda}$$

(6) $$\underline{Y} = (b/6)\frac{(1+2\lambda)}{(1+\lambda)}$$

12.3 Appendix II: Revised Weights

Table 12.1: Spreadsheet for Revised (Improved) Weight Calculations

Gross Weight		***Fuel Used***		***New Weight***	
Wo Guess:	434926.799	**Wf1:**	10873.17	**W1:**	424053.629
We/Wo:	0.4910537	**Wf2:**	8958.1329	**W2:**	415095.496
We:	213572.413	**Wf3:**	79698.3352	**W3:**	335397.161
Calculated Wo:	434926.799	**Wf4:**	3689.36877	**W4:**	331707.792
Guess - Calculated:	-1.22E-07	**Wf5:**	1658.53896	**W5:**	330049.253
		Wf6:	6972.29046	**W6:**	323076.962
		Wf7:	2907.69266	**W7:**	320169.27
		Wf8:	3521.86197	**W8:**	316647.408
		Wf9:	1583.23704	**W9:**	315064.171
		Wf:	127054.386		

Appendix III: Project Promotion Video Link

- https://youtu.be/BhcZjfpFztE

Chapter 13: Resources

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